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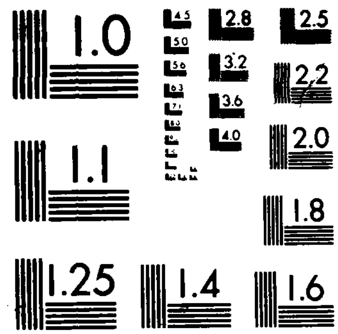

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NONLINEAR ACOUSTICS: NONCOLLINEAR INTERACTION, REFLECTION AND REFRACTION, AND SCATTERING OF SOUND BY SOUND

THIRD ANNUAL SUMMARY REPORT UNDER CONTRACT N00014-84-K-0574

David T. Blackstock

APPLIED RESEARCH LABORATORIES
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24 July 1987

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1 November 1986 – 30 September 1987

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Research on four topics in nonlinear acoustics is described. 1. Dependence of three coefficients of nonlinearity for sea water on pressure, temperature, and density. Computation of the coefficients from a combination of theoretical and empirical relations is in progress. 2. Nonlinear, noncollinear interaction of sound waves. Three journal articles have been written, two on interaction in a rectangular waveguide and one on the coefficient of nonlinearity for collinear and noncollinear interaction. 3. Reflection and refraction of finite-amplitude sound at a plane interface between two fluids. A new form of Snell's law valid for waves of finite amplitude is derived. An experiment to test the implications of the new law is being carried out. 4. Scattering of sound by sound. The classical problem of the secondary radiation produced by interaction of two crossed sound beams is discussed. An experimental test of recent theoretical treatments is being prepared. A preliminary experiment is the measurement of the range dependence of "finger" lobes in the second harmonic radiation produced in the field of a monochromatically driven piston. Keywords:

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I. INTRODUCTION

The research carried out under Contract N00014-84-K-0574, which began 1 August 1984, is primarily in the field of nonlinear acoustics. The broad goal is to determine the laws of behavior of finite-amplitude sound waves, especially to find departures from the laws of linear acoustics. This report covers the 11-month period ending 30 September 1987. See the First Annual Summary Report (85–8)* for the period 1 August 1984 – 31 October 1985, and the Second Annual Summary Report (86-6) for the period 1 November 1985 – 31 October 1986.

The following persons participated in the research:

Graduate students

Charles E. Bradley, M.S. student in Mechanical Engineering

F. D. Cotaras, Ph.D. student in Electrical and Computer Engineering

Daniel L. Edwards, M.S. student in Mechanical Engineering

Andrew J. Kimbrough, M.S. student in Mechanical Engineering

J. A. Ten Cate, Ph.D. student in Mechanical Engineering

Senior personnel

M. F. Hamilton,† Mechanical Engineering Department, The University of Texas at Austin

C. L. Morfey, consultant, Institute of Sound and Vibration Research, University of Southampton, England

W. M. Wright, consultant, Physics Department, Kalamazoo College, Michigan

D. T. Blackstock, principal investigator

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*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 85-8 means the eighth entry in the list for 1985.

†Hamilton received no direct support from Contract N00014-84-K-0574. However, he contributed in various ways to the research reported here. First, his name appears in several of the topics listed in Project B below. Work on these topics began earlier, when he was supported under the contract (see 85-8), or associated with its predecessor, Contract N00014-75-C-0867. Second, he is co-supervisor of Ten Cate's Ph.D. research, which is Project E below.

II. PROJECTS

Projects active during the report period are listed below. For continuity the lettering of the projects follows that used in the Second Annual Summary Report (86-8). Project D, subharmonics and chaos, was not continued this year (see 86-6). Project E is new this year.

A. Nonlinear effects in underwater propagation

B. Nonlinear, noncollinear interaction of sound waves

C. Reflection and refraction of finite-amplitude sound at a plane interface

E. Scattering of sound by sound

The major projects this year were C and E, but considerable time has been spent on Project B.

A. Nonlinear Effects in Underwater Propagation

The main work in this general area was completed in 1986; see the Second Annual Summary Report (86-6). Only the special task on dependence of three coefficients of nonlinearity on pressure, temperature, and salinity is still active. It is being carried out by Morfey and Cotaras (Kimbrough also assisted during the early stages). Most of the progress in the current report period occurred during the spring when Morfey spent about four weeks at ARL:UT.

The three nonlinearity coefficients of interest are the first-order coefficient β, a second-order coefficient, and the Gruneisen parameter. They are computed from formulas involving density, sound speed, and specific heat at constant pressure. The latter quantities are in turn computed from empirical relations for which the inputs are pressure, temperature, and salinity. However, a variety of empirical relations are available. We are considering ten: four for density, three for sound speed, and three for specific heat. Our goal is to calculate the three coefficients and determine the extent to which their values change when different combinations of the empirical relations are used. The library of subroutines, which includes not only the empirical relations themselves but also their derivatives with respect to temperature and pressure, is large, of order 80.* The precision of each subroutine has been tested.†

*In the Second Annual Summary Report (86-6) it was noted that the various databases needed to calculate the three coefficients had been compiled. At that time we were planning to use numerical differentiation techniques. We have since found, however, that the precision of these techniques is unacceptable in some cases. Our current procedure is to algebraically differentiate each function, twice in some cases, and then implement the derivatives as separate routines.

†The verification procedures varied from simple comparisons of published check values, which are provided in the journal articles that deal with the empirical relations to special routines to verify (by integration) the various derivative routines.

Morfey has written an extensive exposition of the theory of the calculations. It is expected that the task will be completed by the end of Morfey's visit next spring.

B. Nonlinear, Noncollinear Interaction of Sound Waves

This project too has largely been completed. Work during the present report period has been limited to writing and/or revising journal articles on the following topics:

(1) Distortion of a single wave, monochromatic at the source, propagating in the 1,0 mode in a rectangular waveguide (called Case A in the Second Annual Summary Report (86-6)). A manuscript by Hamilton and Ten Cate has been written and will be submitted to the Journal of the Acoustical Society of America before the end of the report period (87-6).

(2) Interaction of waves in the 0,0 and 1,0 modes in a rectangular waveguide (called Case B in the Second Annual Summary Report (86-6)). The journal article by Hamilton and Ten Cate on this subject appeared in the June 1987 issue of the Journal of the Acoustical Society of America (87-2).

(3) Angular dependence of the coefficient of nonlinearity (called task (3) in the Second Annual Summary Report) (87-6). A journal article by Hamilton and Blackstock has been accepted with minor revisions by the Journal of the Acoustical Society of America and is expected to appear before the end of 1987 (87-1).

In addition, an article by Ten Cate and Blackstock on the noncollinear suppression of sound by sound is in preparation. This article will be based mainly on Ten Cate's M.S. thesis research (84-2).

C. Reflection and Refraction of Finite-Amplitude Sound at a Plane Interface

Our work on this project during the previous year is reviewed in the Second Annual Summary Report (86-6). Briefly, a literature survey revealed no general analysis of reflection and refraction of an obliquely incident finite-amplitude wave. The analytical work that has been done is limited to a second-order perturbation analysis for an initially sinusoidal wave [1-4]. Even this very restricted analysis leads to exceedingly complicated mathematical expressions.

Continuing the literature review this year, Cotaras has re-examined the works by Ginsberg and considered several additional relevant works [5-10]. Cotaras's conclusions are the same as those cited in the Second Annual Summary Report (86-6), that is, that despite apparent similarities the plate vibration problem and the reflection-refraction problem are different. The plate vibration is caused by an external driving force and is, in the second-order approximation, coupled to the acoustic response of the fluid. The literature survey did, however, bear some fruit in that the same method of analysis used to solve the plate vibration problem might be useful in solving the reflection-refraction problem. The references on the plate vibration problem

are very useful for the material contained therein on the methods of renormalization and multiple scales.

Our approach is based on Snell's law. First, making some apparently reasonable approximations, we derive a form of Snell's law that is valid for finite-amplitude waves infinite on a plane interface. Second, the new form of Snell's law is to be exploited by making predictions about the waveform of the transmitted wave at various distances from the interface. Finally, the predictions are to be tested by an experiment. The derivation has been done and is presented below. The exploitation is just beginning, and concurrently the apparatus for the experiment is being developed.

The derivation of Snell's law for a finite-amplitude wave is now presented. A plane wave obliquely incident on a plane interface between two fluids is considered. Let c_0 be the small-signal sound speed, β the coefficient of nonlinearity, and u the particle velocity of a given wavelet (point on the waveform). Our basic assumption is that the progressive, plane wave law for the propagation speed,

$$\frac{dx}{dt} = c_0 + \beta u \quad , \tag{1}$$

may be used for both the incident and transmitted wave fields. In fact, this relation can apply to the incident wave only so long as the incident wave is not overlapped by the reflected wave. When overlap occurs, the two waves interact (superposition applies only to small-signal waves) and, strictly speaking, Eq. (1) is no longer valid. For relatively weak waves, however, particularly if the incident wave is a pulse so that the time and spatial region of the overlap are small, Eq. (1) is still expected to hold as a good approximation. As for the transmitted wave, since it is truly progressive, one's first impression may be that Eq. (1) is applicable without reservation. The problem is, as our derivation below shows, that the transmitted field is not really plane. However, because the departure from planar propagation is not expected to be great, the use of Eq. (1) is still justified as a good approximation. Moreover, corrections for nonplanar (but still progressive) propagation are in principle easy to make.

See Fig. 1. The y axis is the interface between fluids 1 and 2, which have static densities ρ_1 and ρ_2, small-signal sound speeds c_1 and c_2, and nonlinearity coefficients β_1 and β_2, respectively. The time waveform of an arbitrary incident pulse is shown in the inset. We focus attention on wavelet a, which is characterized by particle velocity (in the direction the incident wave is traveling) u_{ia}. The wavefront for this wavelet is shown as dashed line WW'. Two rays (solid lines) R_1 and R_2 are shown, which make an angle of incidence θ_i with the normal (x axis) to the interface in fluid 1. Rays R_1 and R_2 are at an angle of transmission θ_t in fluid 2. At time $t = 0$ the wavefront is at position AA' (its continuation in fluid 2 is AA''), ray R_1 intersects the interface at point A, and ray R_2 is at point C. At time Δt later the wavefront has progressed to position BB' (continued as BB'' in fluid 2), and ray R_2 intersects the interface at point B. The distance traveled by the wavelet along path CB is, by application of Eq. (1),

$$CB = (c_1 + \beta_1 u_{ia})\Delta t \quad .$$

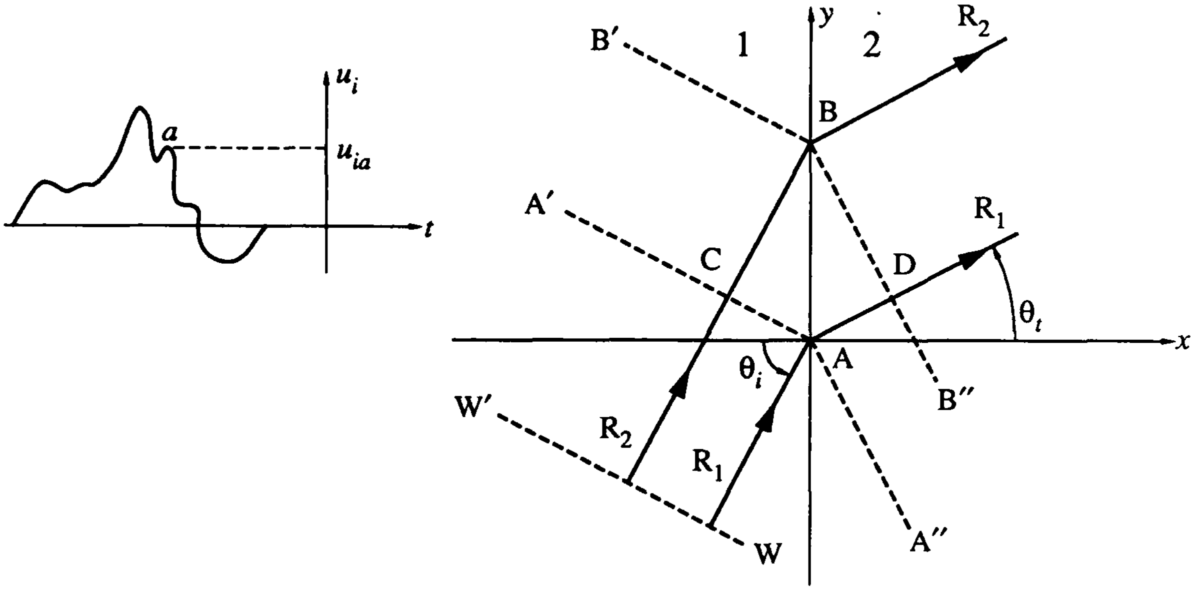

FIGURE 1. WAVEFRONTS AND RAYS FOR INCIDENT AND TRANSMITTED WAVES. FOR CLARITY THE REFLECTED WAVE FIELD IS NOT SHOWN.

The trace distance the wavelet has traveled along the interface is

$$AB = \frac{CB}{\sin\theta_i} = \frac{(c_1 + \beta_1 u_{ia})\Delta t}{\sin\theta_i} \quad . \tag{2}$$

Next consider what is happening to the rays and wavefronts in fluid 2 during time Δt. The transmitted wavelet, now characterized by particle velocity u_{ta} (the value of which must be computed from the transmission characteristics to be worked out later),* travels from A to D along ray R_1. The distance is, again by application of Eq. (1),

$$AD = (c_2 + \beta_2 u_{ta})\Delta t \quad ,$$

and the trace distance is

$$AB = \frac{AD}{\sin\theta_t} = \frac{(c_2 + \beta_2 u_{ta})\Delta t}{\sin\theta_t} \quad . \tag{3}$$

Combination of Eqs. (2) and (3) yields

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{c_2 + \beta_2 u_{ta}}{c_1 + \beta_1 u_{ia}} \quad . \tag{4}$$

This is Snell's law for a finite-amplitude wave. We have, of course, assumed that wavelet a is not part of a shock as it travels through fluids 1 and 2.

The implication of Eq. (4) is that the angle of refraction depends on the wavelet particle velocity. In particular, peaks of a wave refract at one angle, and troughs at

*Again the particle velocity meant is that in the direction of the ray.

another. This means that the wavefronts for the various wavelets in fluid 2 are not parallel. We come to the conclusion referred to earlier that the transmitted wave field is not planar in the true sense of the word. Nevertheless, the time waveform at a given point in fluid 2 may be computed simply by keeping track of the arrival of the various wavefronts.

The derivation is not given here; it is clear that the law of specular reflection,

$$\theta_r = \theta_i \quad , \tag{5}$$

where θ_r is the angle of reflection, will also need revision. Additional theoretical work that must be done is to use the pressure and particle velocity boundary conditions at the interface to determine the reflection (R) and transmission (T) reflection coefficients.* The transmission coefficient is needed to express u_{ta} in terms of u_{ia} in Eq. (4). Similarly, the reflection coefficient will be needed in conjunction with the revised version of Eq. (5).

Some local nonlinear effects have been overlooked in our derivation of Snell's law. We have assumed that the interface stays fixed during the reflection-refraction process. In fact, it does not. It moves, in fact undulates, so as to follow the fluid displacement fields on either side. Moreover, as the interface undulates, so does its normal. The finite displacement of the boundary and the deviation of the normal from being parallel to the x axis are phenomena that are neglected in small-signal theory. We wish to neglect them here as well, on the grounds that the effects they produce are negligible compared to the distinction between Eq. (4) and the small-signal form of Snell's law. However, in order to assess the importance of these phenomena (and also the nonlinearity of the impedance relation), Cotaras has commenced an analysis of the reflection-refraction problem by using a straightforward perturbation expansion. The fluids are assumed to be lossless, homogeneous, irrotational, and initially at rest. The analysis has been completed for the one-dimensional (normal incidence) case and is in process for the two-dimensional (oblique incidence) case. In both cases the procedure is the same: A conventional perturbation expansion is applied to the hydrodynamics equations and a state equation valid for perfect gases. After the boundary conditions at the interface are first specified in Lagrangian coordinates, they are transformed to Eulerian coordinates and the perturbation expansion is applied. The $O(\epsilon)$ and $O(\epsilon^2)$ systems are then solved in terms of the velocity potential. Results so far confirm that it is appropriate to neglect the local nonlinear effects.

The experiment to test Eq. (4) and its ramifications is being prepared. The current design is as follows. The acoustic source (a spark at the focus of a parabolic dish, which produces a plane N wave) is to be in air (c_1 = 343 m/s), and the receiver, one of our very wide bandwidth microphones [12], is to be in helium (c_2 = 1000 m/s). The two gases are to be separated by a very thin sheet of mylar or perhaps latex rubber. Unfortunately, even the thinnest membranes considered so far are not acoustically transparent to the N wave. Considerable transmission loss occurs at the higher frequencies. We considered performing the experiment in two immiscible

*Many years ago some work was done on this problem for the case of normal incidence[11].

liquids, e.g., water and oil, which would require no separating membrane. But an experiment with two liquids would have its own drawbacks, not the least of which would be expense. We have decided to proceed with the helium-air experiment and simply take account of the presence of the membrane. Much positioning equipment has been acquired, and important pieces of hardware have been built and tested.

One particular experiment Cotaras has proposed is to direct the incident N wave on the interface at the angle of intromission θ_0 (analogous to Brewster's angle in optics). Since little or no reflection will be generated in this case, the incident wave field will be truly progressive everywhere. The use of Eq. (1) for the incident wave is then justified without reservation. Of course, since the small-signal formula for θ_0 is not expected to be valid (we expect θ_0 to be wavelet dependent, just as θ_t is), some reflected signals should appear. Even so, however, they should be weak enough not to disturb the incident field very much.

E. Scattering of Sound by Sound

Ten Cate's new doctoral project is the scattering of sound by sound. The question is whether, when two intense sound beams intersect, their nonlinear interaction produces secondary radiation outside the region of interaction. In the most commonly considered problem, the two intense beams are of different frequency and the secondary radiation of interest is at the sum and difference frequency. Since the opening shot (1956) by Ingard and Pridmore-Brown [13], who claimed to have observed the scattered radiation, and Westervelt's contention (1957) that no such scattering exists [14,15], the question has provoked interest and controversy, seemingly without end. Many experiments have been done (see, for example, Refs. 16-21) and theoretical analyses presented (see, for example, Refs. 22-24), but the issue is still unresolved. Why tackle this ancient chestnut? What new angle do we have that offers promise for real progress?

The answer is that J. N. and S. Tjøtta have recently developed a comprehensive theory of sound wave interactions that holds promise for settling the question [25-28]. The key is including all the effects of diffraction. When diffraction is taken into account, the results indicate that a scattered secondary field does exist. Recent work by Darvennes and Hamilton [29,30] provides a closed form expression for the scattered field and shows it to be measurable. Ten Cate's work is aimed at finding the scattered field predicted by the Tjøttas and by Darvennes and Hamilton.

Although the necessary literature survey has been completed, work on the experiment has been slowed by Ten Cate's preoccupation with the journal articles described in Project B. Various components of the apparatus for the experiment have been acquired and tested.

Ten Cate is presently working on a preliminary experiment, in which he will measure the propagation curves for the finger lobes in the second harmonic radiation produced when a piston source is driven at a single frequency. The lobes represent sound scattered by sound (in fact, self-scattered) in the sense that the finger radiation is outside the beam of the primary radiation. Although finger radiation has

been observed previously [31,32], its decrease with distance has not been measured. Since Bernsten, Tjøtta, and Tjøtta [35] have given a prediction of the decrease, the preliminary experiment will provide a first test of the Tjøttas' theory.

F. Miscellaneous

An article by Kuntz and Blackstock on saturation of sound in an air-filled porous material appeared in the June issue of the Journal of the Acoustical Society of America (87-3). W. M. Wright's article on thermoacoustic radiation by a current-carrying wire is scheduled to appear in the August issue (87-5).

III. SUMMARY

During the current report period, 1 November 1986 - 30 September 1987, we have been occupied with four projects. First, in the area of nonlinear effects in underwater propagation, we are carrying out a computation of three coefficients of nonlinearity for seawater as a function of pressure, temperature, and density. Second, on the problem of nonlinear, noncollinear interaction of sound waves, primarily in a rectangular waveguide, three journal articles have been written. One has already been published; the other two are in the review process. The third project is the reflection and refraction of finite-amplitude sound at a plane interface between two fluids. A modified form of Snell's law has been derived, and an experiment to test it is in preparation. Fourth, experimental work on the scattering of sound by sound has begun. The initial experiment is on self-scattering. The goal is to measure the range dependence of the finger lobes in the second harmonic field developed by a monochromatically excited piston.

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JS	=	submitted for journal publication	0867	means	N00014-75-C-0867, ended 8-31-84
O	=	oral presentation			
P	=	paper in a proceedings			
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TR	=	technical report			

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